under a pressure of 40 cm mercury and to 70 percent absorption under a pressure of 9 cm. This behavior is quite different from that of water vapor. It can be inferred from theoretical arguments that the individual lines which compose the absorption band of CO_2 must be rather close together. One can prove that if the cores of the lines do completely overlap, the absorption becomes independent of pressure. In the CO_2 band this condition is approximately realized. For computations of atmospheric transmission we may neglect the pressure dependence of the absorption in cases in which no great precision is required. There seem to be no other constituents of the atmosphere which absorb, appreciably, infrared radiation; ozone (**19**) in the concentrations in which it is present in the atmosphere is almost transparent in the far infrared.

CONCLUSIONS

In the preceding section we have tried to give an exhaustive enumeration of all the effects which under atmospheric conditions could possibly modify the absorption coefficient of water vapor. The main effect is the dependence upon pressure and temperature treated in the first section. There are two accessory features to be taken into account. The first is the appearance of gaps of partial or complete transparency in spectral regions which in Simpson's method are still treated as absorbing continuously; this refers especially to the region beyond 15μ. The gaps will appear at places intermediate between two lines; these effects can be calculated from the formulae given above, when somewhat more precise values of the line intensities are known. The second effect is the change of the total line intensities due to the change in concentration of the corresponding molecular states.

All the effects which have been mentioned in this paper tend to *decrease* the absorption coefficient as compared with the values used so far, especially in the higher levels of the atmosphere. Our results lend themselves to a number of applications concerning the absorption of terrestrial and solar radiation by the atmosphere which will be given at a later time. We might confine ourselves here to a few preliminary remarks. Simpson assumes in his work a content of about 0.3 mm of precipitable water for the whole of the stratosphere. Now under the reduced pressure this layer has an absorption corresponding to less than one-fifth of this amount of water under normal pressure. It follows that the stratosphere is practically transparent with the exception of the very narrow spectral regions occupied by the line cores. The flux of radiation through the stratosphere takes place principally in the cores; the radiation is therefore of a different spectral composition from that emitted by the troposphere. No direct inferences about the thermal state of the stratosphere can thus be drawn from a knowledge of the radiative transfer in the troposphere.

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ON PILOT BALLOONS AND SOURCES OF LIGHT FOR HIGH ALTITUDE UPPER-WIND OBSERVATIONS

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The research described herein was begun in December 1934, in response to military meteorological problems, and continued as occasional opportunity offered until September 1937 when the work was necessarily terminated on account of administrative reasons. Due to these limitations, some of the data obtained are incomplete, and the results presented should be regarded as first approximations. They are nevertheless thought to be of general value to meteorologists, because the field has previously been little explored.

When cloudiness or poor visibility exists in the lower levels, upper wind determinations to high altitudes can be made only by means of the yet experimental radio pilot balloon,[1] or by means of expensive military techniques. The radio pilot-balloon problem is a complicated one, and its two-dimensional solution with a desirable precision of direction (1/10 of 1 degree) will probably require many years. The research described herein is concerned only with the far more simple problem of determining upper winds during the day or night to altitudes of 15,000 to 40,000 feet in good visibility under clear skies or high cirriform clouds. Recent aviation trends toward flying in the substratosphere, 20,000 to 30,000 feet, have brought this problem into immediate practical importance. In addition, high-altitude upper-wind observations are often useful to a weather analyst and forecaster.

PILOT BALLOONS

Standard 6-inch pilot balloon.—The standard 6-inch pilot balloon, as used by the United States Weather Bureau and the Army Meteorological Service, weighs about 1 oz. (30 g) and costs about 10 cents. Inflated with hydrogen (cost about 10 cents) to a free lift of 4.66 oz. (137 g), corresponding to a sea-level diameter of about 2½ feet, it rises at an average rate (except in the zone of lower-level turbulence) of about 200 yards per minute. White, red, and black colors are available for use, respectively, under clear sky, cirriform clouds or darker clouds. A normally inflated balloon usually bursts at an altitude around 30,000 to 40,000 feet; but due to its small size, slow rise rate, increasing winds at upper levels, and the

[1] W. H. Wenstrom, Radiometeorography as Applied to Unmanned Balloons, MONTHLY WEATHER REVIEW, vol. 62, July 1934.

optical limitations of standard theodolites, even under clear skies the balloon is usually lost to view (unless the upper winds are exceptionally light) at an altitude below 20,000 feet.

Balloon clusters and day beacons.—During the winter of 1934–35 at Bolling Field, D. C., and Aberdeen Proving Ground, Md., balloon clusters of various sorts were tried in an attempt to attain higher altitudes than were practicable with a single 6-inch balloon. A cluster of three or four white or red, or both, balloons, snugly tied neck to neck, was tried; also a tandem cluster of three balloons spaced about 20 feet apart along a string, the upper balloon being somewhat overinflated; results were slightly better than with a single balloon. Somewhat better results were obtained by hanging a "day beacon" (a large open cylinder of glazed white paper on a frame of No. 16 copperclad steel wire, size about 20 by 30 inches, weight about 2 oz., reflecting sunlight better than the balloons) about 50 feet below the cluster with a string. It is possible[2] to connect some device such as a water-filled copper tube (or perhaps a sealed glass vial) in the suspended string, so that the day beacon will drop when the freezing (0° C) level is reached. At night we used some four-candle lanterns (fully described below) with 6-inch balloon clusters.

All these early experiments served to show, however, that what we really needed was a larger pilot balloon. A 9-inch pilot balloon was used for high-altitude work by the Army Meteorological Service during the war, but was later discontinued. Large sounding balloons were available, of course, but were prohibitively expensive for ordinary upper wind observations.

Twelve-inch pilot balloon.—During the winter of 1934–35 Maj. A. H. Thiessen, Chief of the Army Meteorological Service at that time, set up specifications for a 12-inch pilot balloon, to be manufactured by a process of coagulation of latex on outside of spherical mold. Approximate characteristics:

Twelve-inch pilot balloon (day):
- Balloon weight: 2¾ oz. (80 g).
- Free lift: 15¼ oz. (430 g).
- Average rise rate: 300 yd./min.
- Average bursting altitude: 40,000 to 50,000 feet.

(Night):
- Four-candle lantern weight: 5¼ oz. (150 g).
- Free lift: 18 oz. (510 g).
- Average rise rate: 220 yd./min.
- Average bursting altitude: above 25,000 ft.
- Also used with 7½ oz. 8-candle lantern, rising at 225 yd./min. when inflated to 22 oz.

During 1935 and 1936 about 250 ascents were made with this balloon at Bolling Field, Aberdeen Proving Ground, and at the temporary Stratocamp in South Dakota.[3] Best results were naturally obtained in the clear air of the West. The 12-inch balloon could be seen farther away than the 6-inch balloon, and its greater rise rate resulted in higher altitude for a given distance out. Double-theodolite day runs to 40,000 feet were easily made in light upper winds; heights greater than 20,000 feet could be reached even in high winds. At night the 12-inch balloon with a 4-candle lantern performed considerably better than the 6-inch balloon with a single-candle lantern; one run under favorable conditions was followed (by single theodolite) to an (assumed) altitude of about 27,000 feet above station or 31,500 feet above sea level. Large pilot balloons of this type, made by the latex-coagulation-on-outside-of-spherical-mold process though expensive (perhaps $2 per unit; hydrogen cost perhaps 30 cents per unit), are uniform in size, shape, and thickness. Their rise rates are correspondingly uniform, and suited to single-theodolite observations.

Sixteen-inch pilot balloon.—About 1936 a 16-inch (100 g) pilot balloon became available. The process consisted of spinning latex to general balloon shape inside a small spherical mold and expanding the hollow ball of latex thus formed, while still soft, to full 16-inch balloon size by air pressure. Compared with the older solid-spherical-mold process, this air-expanded process produces balloons that are considerably lighter and far cheaper (perhaps 50 cents per unit; hydrogen cost perhaps 50 cents per unit), but apparently less uniform. The balloons tested, at least, were not very uniform in size, shape or thickness; later models, it is understood, have been improved considerably in these respects. Practically, such inequalities result in an appreciable percentage of premature bursts; and (despite uniform inflation) in considerable and unpredictable variations of rise rate, necessitating double-theodolite observations. Far outweighing these disadvantages, however, is the high rise rate and lifting power of the 16-inch balloon.

During 1936 and 1937 we made about 200 test ascents at Bolling Field and Aberdeen Proving Ground with the 16-inch balloon, ascending both by itself and in combination with various weights and light sources. Preliminary tests showed that rise rates around 400 yd./min., attained with free lifts around 40 oz., were optimum; lower lifts and rates did not materially reduce premature bursts, while higher lifts and rates did increase them. As 400 yd./min. is a round number exactly twice the standard rise rate for 6-inch balloons, it was soon adopted as standard.

The highest free lift used was about 44 oz., which in winter gave rise rates around 400 yd./min. at the lower levels for the balloon alone. Above 10,000 feet this rise rate usually increased gradually, perhaps by 10 percent at altitudes around 30,000 feet, the increase being apparently due to some decrease in tumbling and oscillation as well as increase of the volume/area ratio. In summer the rise rate was higher, averaging 450 yd./min. in the lower levels for a free lift of 42 oz.; the upper level increase was less marked, perhaps due to steeper lapse rates in the summer atmosphere. Differences between the average rise rate of individual ascents amounted to 10 percent or so, occasionally to 20 percent. During an ascent, the rise rate was likely to vary from level to level by 10 to 20 percent. As a working free lift to approximate the 400 yd./min. rise rate through all levels under most conditions with the 16-inch balloon alone, 40 oz. appears to be the best figure. Summarizing approximate characteristics:

16-inch pilot balloon (day):
- Balloon weight: 3½ oz. (100 g)
- Free lift: 40 oz. (1,130 g)
- Average rise rate (balloon only): Around 400 yd./min.
- Average bursting altitude: 40,000 to 50,000 ft.

About 100 daytime ascents were made with the balloon alone under various conditions, at least 30 being checked by double theodolite to altitudes above 30,000 feet. Under clear skies and through average upper winds the white balloon could be followed with standard theodolites to distances of 20 or 30 miles and to altitudes of 40,000 to 50,000 feet. One observation in March extended to 36,000 feet altitude through winds of 90 m. p. h. at 10,000 ft., 70 m. p. h. at 20,000 ft., and 120 m. p. h. at 30,000

[2] J. F. Brennan—"A method of determining the altitude of the freezing point"—Mo. Wea. Rev., vol. 59, February 1931.

[3] W. H. Wenstrom—"Some Interesting Pilot Balloon Observations"—*Bull. Am. Met. Soc.*, vol. 16, Nos. 8-9, August-September 1935.

ft.; so it is probable that the 16-inch white balloon assures daytime, clear sky observations to 30,000 feet in any ordinary winds.

In 1937 some red 16-inch balloons were obtained, and tested against white balloons to altitudes around 30,000 feet. Under clear skies the white balloon gave a sharper image and could be followed to somewhat higher altitudes, though the red balloon proved nearly as good. Under cirriform clouds the red balloon was easier to follow, but with due care the white balloon could also be followed to high altitudes.

In connection with development work on the light sources described below, ascents were made with 16-inch balloons carrying various weights. The addition of any weight up to 5 or 10 oz., hung by a string 50 ft. below the balloon to minimize swinging, had much less effect on rise rate than one might expect; apparently the weight stopped tumbling tendencies and pulled the balloon into a more streamlined shape, thereby compensating for the loss of free lift. With a weight of 5 oz. or so, indeed, it seemed necessary, on the average, *to decrease* the free lift in order to obtain the same rise rate in lower and middle levels. With the weight, however, there was little if any increase of rise rate with altitude; at night, in fact, the rate usually decreased somewhat with altitude. In general, the rise rates with weights appeared to be more uniform at all times, and suggested the idea (which could not be thoroughly investigated) that dummy weights (say 5 oz. or so of some light, cheap material such as pasteboard) might profitably be used for better uniformity in daytime ascents. As an immediate and fortunate corollary of the balloon-plus-weight performance, it was evident that fairly heavy luminous sources could be carried up at 400 yd./min without overinflating the balloon.

SOURCES OF LIGHT

Six-inch balloon lights.—Standard lights for 6-inch balloons, as used by the United States Weather Bureau, are of two kinds: A single-candle lantern and a small electric light.

The single-candle lantern consists of a candle about ¾ inch (diameter) by 1 inch (long), candlepower about 1.0 and quite constant, burning time about 35 min.; mounted in the bottom of a cylindrical paper lantern about 4½ inches (diameter) by 8 inches (long), transmission of paper about 80 percent; weight complete about ½ oz. and cost perhaps 2 cents. Under average-visibility, clear-sky conditions, this lantern can be followed with a standard theodolite to distances of 3 to 6 miles, corresponding in various winds to altitudes of 6,000 to perhaps 15,000 feet above station at a rise rate of 200 yd./min.

The standard electric light consists of two 1.5-volt dry cells, size ½ inch by 1⅜ inches, and a flashlight bulb rated at 2.3 volts, 0.25 amps.; open circuit voltage 3.0; at start the closed circuit voltage is 2.3, the wattage 0.6, and the candlepower about 1; at assumed cut-off, after about 30 minutes, the voltage is 1.5, the wattage 0.3, and the candlepower about ¼; the light weighs about 1 oz. and costs perhaps 12 cents. Compared with the standard candle lantern, the electric light gives comparable altitude performance; it also eliminates fire hazard.

Four-candle lantern.—Any study of the problem of reaching higher altitudes with night upper wind observations at once suggests brighter light sources as the most obvious answer. The most promising immediate approach appeared to be an enlargement of the standard candle lantern. Experimentation with various sizes and arrangements of candles and lanterns, including some very large candles made to order, showed that the most practical development was a multiple arrangement of standard candles spaced about 2 inches apart in a completely closed paper lantern large enough so as not to catch fire. To reach distances and altitudes twice as great as those possible with the single candle lantern, at least four times as much light would be needed. The developed lantern had the following characteristics:

Four-candle lantern:
- Cylindrical white tissue paper lantern, 12 inches in diameter by 30 inches long; top and bottom frames, circular with cross pieces, of No. 16 copperclad steel wire soldered together at junctions; hanging wire to balloon string, and safety wire between top and bottom frames, No. 20 soft copper.
- Four-candle holder of ⅜-inch plywood, 3¾ inches square, having four 11/16-inch holes, drilled on diagonals, 17/16 inches from center so as to hold four standard ¾-inch candles, each 3 inches long, with wicks at the corners of a square 2 inches on a side; holder secured to bottom frame of lantern with thumbtacks.
  - Weight complete: 5¼ oz. (150 g approximately).
    - Four candles: 2¾ oz. (80 g).
    - Candle holder: 1 oz. (30 g).
    - Lantern: 1½ oz. (40 g).
  - Candlepower: About 4 to 6.
  - Transmission through paper: About 70 to 80 percent.
  - Burning time: About 50 minutes.
- Four-candle lantern with 16-inch balloon:
  - Free lift: 38½ oz. (1,090 g).
  - Average rise rate: Around 400 yd./min.

While the lantern reaches 30,000 feet in 25 minutes and is usually lost earlier, the 50-minute burning time allows ample reserve for lighting the candles and pasting or clipping closed the bottom of the lantern at leisure, for use at a slower rise rate with a 12-inch balloon or underinflated 16-inch balloon, or for observations to extreme altitudes under very favorable conditions. The lantern is launched with even acceleration so that it will not jerk out of the hand. The launching location must be sheltered from anything greater than light surface winds, which might blow the side of the lantern into the flame. Once released, the lantern almost invariably stays lighted despite the terrific beating it takes from the combined forces of downdraft, humping, and swinging. One lantern, in fact, remained lighted for over a minute in free fall after its balloon burst at high altitude. As the candles burn down, a pool of wax forms on and around the candle holder; this finally ignites and burns away the lower part of the lantern; the air draft then extinguishes the flames entirely, so that, short of premature balloon bursts, the fire hazard is not serious.

Four-candle lanterns were used in about 60 test ascents, of which about 30 were night double-theodolite runs using 16-inch balloons. The large lantern presents a large lighted surface easily focused into a clear image. Several tests showed that it can be seen two or three times as far away as the single-candle lantern; and rising at 400 yd./min., it gives observations to altitudes two or three times as great as those possible with a single-candle lantern rising at 200 yd./min. Our best night observation with the four-candle lantern extended to 25,500 feet altitude above station, checked by double theodolite on the 20th minute when the lantern was about 13 miles distant and encountering 70-mile winds. A single-candle lantern released within the hour, under identical conditions, could be followed only to 8,000 feet altitude, where it was lost in 30-mile winds. On a winter night when winds above 10,000 feet were 60 to 90 m. p. h., four-candle lanterns were followed to 15,000 feet altitude, as against 7,000 feet for single-candle lanterns. All these tests, as well as the tests described hereafter, were made near the east coast where visibility is rarely very good; in the clear air of the

FIGURE 1.—Sixteen-inch pilot balloon inflated to 38½-oz. free lift, with 4-candle 5¼-oz. lantern, permitting night upper wind observations to altitudes of 15,000 to 30,000 feet.

FIGURE 2.—Sixteen-inch pilot balloon inflated to 42-oz. free lift, with 7-oz. 40-minute experimental pyrotechnic flare.

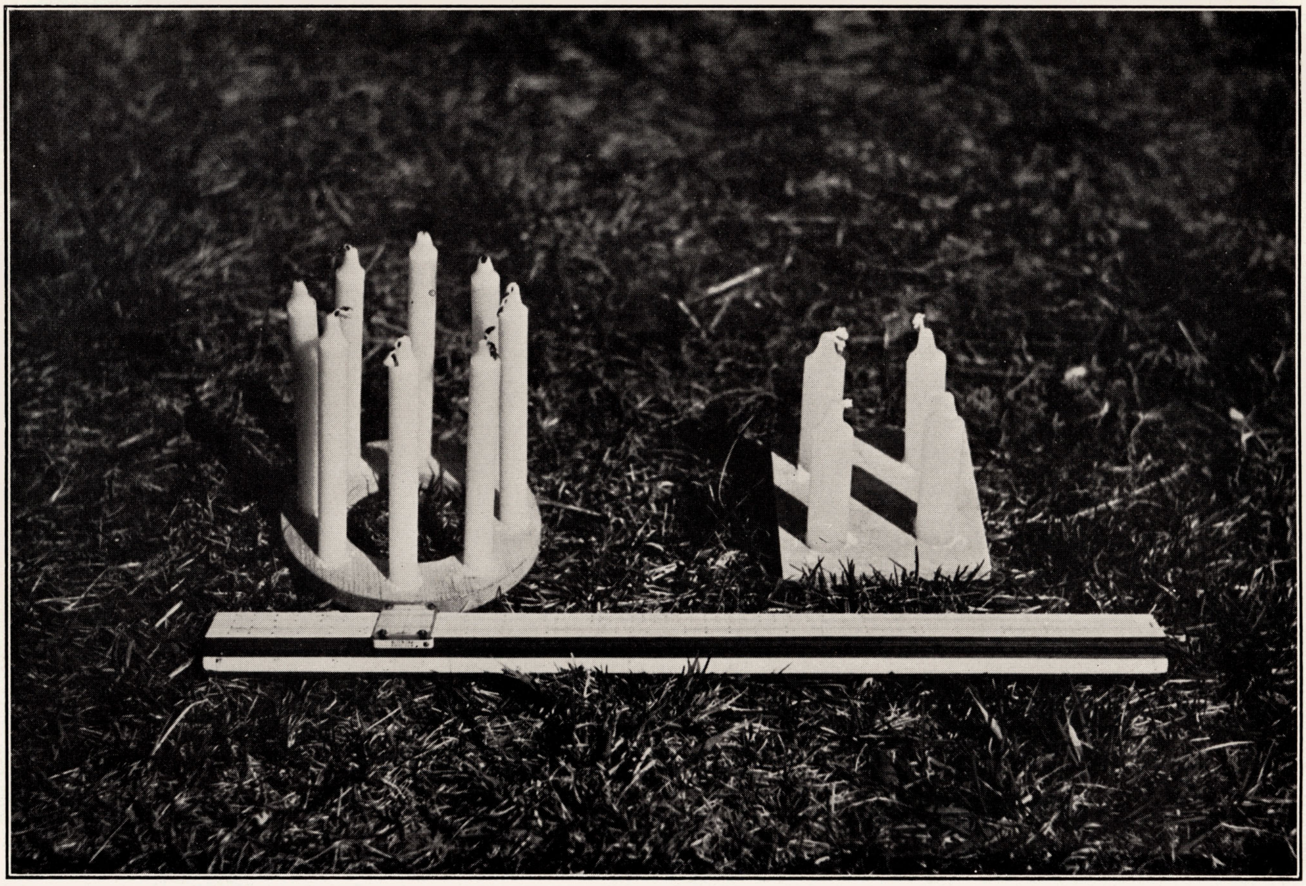

FIGURE 3.—Right: Four-candle unit as used in four-candle lantern. Left: An experimental eight-candle unit. Size comparison: 16-inch slide rule.

FIGURE 4.—Left: 3-watt 9-oz. electric light source giving night upper wind observations to altitudes of 15,000 to 25,000 feet. Right: Acetylene light source.

West, better results might be expected. Summarizing, we might say that the four-candle lantern can be followed by standard theodolites under favorable conditions to distances of 8 to 15 miles, corresponding in various winds to altitudes of 15,000 to 30,000 feet at a rise rate of 400 yd./min.

Six- and 8-candle lanterns.—In an effort to better the performance of the four-candle lantern and explore the limits of multiple-candle combinations, eight-candle and six-candle units were developed for use with the 12-inch by 30-inch paper lantern described above, which in itself represented a desirable limit of overall size.

The eight-candle holder consisted of a plywood ring drilled with eight ½-inch holes at 1½-inch intervals around a 4-inch circle, in which eight 17/32-inch votive candles could be fixed. Candles 3½ inches long gave a lantern burning time of about 25 minutes and a total weight of about 5½ oz.; with 5-inch candles it burned about 35 minutes and weighed about 7½ oz. This lantern gave some increase of light over the four-candle type, but sacrificed too much in simplicity and reliability. It caught fire easily in light surface winds, and in some balloon tests went out at middle altitudes.

The six-candle lantern was developed to give somewhat more light than the four-candle lantern without sacrificing simplicity or reliability. To keep the weight within reasonable limits, however, it was necessary to sacrifice reserve burning time. Summarizing approximate characteristics:

Six-candle lantern:
- Cylindrical white tissue paper lantern, as described above.
- Six-candle holder of ⅜-inch plywood, 5½-inch ring with 2½-inch center hole, having six 11/16-inch holes drilled at equal intervals around a 4-inch circle so as to hold six standard ¾-inch candles each 2 inches long with wicks spaced 2 inches apart around the circle.
- Weight complete: 6½ oz. (185 g).
  - 6 candles: 3 oz. (85 g).
  - Candle holder: 2 oz. (55 g).
- Candlepower: about 6 to 8 (less 20 to 30%).
- Burning time: about 25 minutes.

Six-candle lantern with 16-inch balloon:
- Free lift: 40 oz. (1,130 g).
- Average rise rate: Around 400 yd./min.

In addition to ground tests, only three double-theodolite night balloon ascents could be made with the six-candle lantern in the time available. In one comparative test under fair conditions the six-candle lantern was followed to 19,000 feet altitude as against 16,000 feet for the four-candle lantern. On another comparative test, both went to about 24,000 feet. By saving weight on the candle holder and lengthening the candles somewhat, the burning time of the six-candle lantern could perhaps be extended to 40 minutes, keeping the total weight under 7 oz. In its present form, the six-candle lantern appears to give slightly better performance than the four-candle lantern, particularly when visibility is only fair.

Another promising development that could not be completely tested was the four eight-candle lantern, which offered the very desirable quality of increasing candlepower. Characteristics:

Four eight-candle lantern:
- Paper lantern as described above.
- Candle holder: Same as in four-candle lantern.
- Four ¾-inch candles, each 2½ inches long, are set in the four holes, same as in four-candle lantern. In addition, four ¾-inch candles, each 1¼ inches long, are set on the diagonals just inside of, and tangent to, the outer candles. Only outer candles are lighted at start; inner candles ignite from them after about 20 minutes.
- Weight complete: About 6¼ oz. (180 g).
- Candlepower: About 4 to 10.
- Burning time: Around 25 minutes. 400 yd./min. rise rate with 16-inch balloon given free lift of about 40 oz. (1,130 g).

No air tests could be made with this lantern in the available time. Ground tests (of candle unit in open air) showed candlepower about 4 at start, increasing to 5 and 6 within 15 to 20 minutes (due to mutual heating of four candles). At 20 minutes the first inner candle ignited; the second ignited at 21 minutes, raising the total candlepower to 8; the third lit at 23 minutes; the fourth lit at 25 minutes, raising the total candlepower to 9–10; at 28 minutes, two candles had burned down to the wood holder. Whether the inner candles would ignite properly in the lantern during a free asecnt, is not known; it is believed that some of them would, at least.

The large candle lanterns described above, compared with other possible light sources of comparable power, have several advantages: Universal availability of materials, low cost (about 6 cents), harmlessness on descent, and reliability. Of the three flame-type light sources that we tested, the candle lanterns alone remained lighted to altitudes above 20,000 feet. All the multiple-candle lanterns, also, have the desirable quality of increasing candlepower in some degree. The disadvantages of large candle lanterns are: Slight fire hazard, limited candlepower, handling difficulties unless carefully folded, and launching difficulties in high surface winds.

Three-watt electric light.—In order to obtain an electric light source about four times as powerful as the standard 6-inch balloon light, we tested various combinations of batteries and bulbs. For simplicity, only standard units in wide distribution were considered. It was early apparent that any electric light of this type would leave much to be desired in the direction of light weight and sustained candlepower. The best combination appeared to be as follows:

Three-watt electric light:

Battery: Six 1.5-volt dry cells, size 1 inch by 1⅞ inches; six 8-volt auto bulb, rated at 3 watts or 1.5 candlepower; weight complete about 9 oz. (255 g); cost about 40 cents.

Data at start: Open circuit voltage 9.0, closed circuit voltage 7.5, watts 3.4, candlepower about 4 to 5.

Time at assumed cut-off 45 minutes; closed circuit voltage 4.5, watts 1.5, candlepower about two-thirds.

Candlepower at 25 minutes (30,000 feet altitude): about 1.

Three-watt electric light with 16-inch balloon:
- Free lift: 42 oz. (1,190 g).
- Average rise rate: Around 400 yd./min.

In addition to ground tests, five double-theodolite night balloon ascents were made with this 3-watt electric light. Just before launching, the wire leads soldered to battery and bulb, scraped bright, were twisted together. During the first few minutes of any ascent, while the bulb operated at high efficiency above its normal voltage, the light was brilliant blue-white, and so steady that it showed in the theodolite considerably better than its measured candlepower would indicate. Later in the ascent, as the bulb efficiency declined, performance was about equal to, or slightly less than, that of the four-candle lantern. The best night altitude reached was 23,250 feet, when the light was about 10 miles away in 70-mile winds 18 minutes after leaving the ground.

The main disadvantages of the electric light are: Its considerable weight, considerable cost, and its very limited and steadily decreasing candlepower. Weight might be saved, and candlepower held nearly constant, by using specially built batteries of lead-acid type. The 9-oz. unit, falling from several miles altitude when the balloon bursts, would be a hazard to objects on the ground; for this reason a simple parachute, consisting of a cloth 3 feet square, was connected in the string between balloon and light. This parachute functioned satisfactorily when tested in the daytime under a balloon carrying a small bursting charge of black powder attached to the neck, the powder being ignited after about 5 minutes of ascent by about 6 feet of blasting fuse. Also, as dry cells lose their efficiency very quickly at temperatures below about 5° F., some sort of heat-insulating material, such as several thicknesses of paper, has to be placed around the battery. The advantages of the electric light are: Ease of handling, ease of launching regardless of surface wind, steadiness and dependability of the light itself, and absence of fire hazard.

Acetylene light.—This light was developed by A. P. Rehbock. It consists of a 6-inch balloon inflated with acetylene, feeding a V-type burner protected by a conical, aluminum reflector-windscreen. The acetylene balloon hangs, burner downward, by a string from the main balloon; inflated to 12-inch diameter, the small balloon supplies the burner for about 35 minutes; the candlepower is around 20. The total weight is about 1 oz; cost, about 10 cents.

Acetylene lights were tested in five night-balloon ascents, two at a 200 yd./min. rise rate (16-inch balloon; free light 10 oz.), and three at a 400 yd./min. rise rate (16-inch balloon; free lift 38 oz.). At 200 yd./min. the light performed well—certainly much better than a single-candle lantern or small electric light of comparative weight. But the acetylene light flickered badly (at a period of about one-half second), at times disappearing altogether for a moment. Each fade and come-back was so rapid, however, that the light could be easily followed with a theodolite.

At 400 yd./min. the acetylene light went out in all three tests, one at a few hundred feet, one at 7,000 feet, and one at 14,000 feet. From these incomplete data, it would appear that the present form of acetylene light is not reliable at the high rise rates which are necessary to reach high altitudes in high winds. Perhaps changes in design, such as an improved reflector-windscreen, would remove this defect. The acetylene light's advantages are light weight, low cost, considerable candlepower; its disadvantages are difficulty of handling, inflation, etc., flickering, and (at present) unreliability.

Pyrotechnic flare.—At the Stratocamp in June 1935, while experimenting with 12-inch balloons and four-candle lanterns, we made several night balloon tests with small, standard railway flares. The ¾-inch, 10-minute flare weighs about 5 oz., and burns with a brilliant red light of more than 200 candlepower; our night balloon tests showed it to be far superior to any other light source during its short burning time. In spite of some fading, the light was so powerful that it could be easily picked up with the naked eye at a distance of 3 to 5 miles. The problem was to develop a red flare that weighs less than 10 oz., and burns at least 30 minutes under a balloon rising at 400 yd./min., with candlepower at least 50 at the start and preferably increasing gradually to several hundred as the balloon rises. The problem is still unsolved, despite considerable work by experts in the fireworks field, but considerable progress has been made.

Other pyrotechnic lights, such as magnesium ribbon, magnesium flares, and sparkler material were considered, experimented with, and dropped in favor of the more promising red flare; red light penetrates haze best, and is easily distinguished from stars. Over a period of more than a year, samples of four flare models were submitted, each in some respects an improvement on the preceding one.

The first flare model embodied a flare tube around 50 inches long; its small (initial) end diameter was about 3/16 inch (the smallest diameter that would burn evenly and reliably in still air), increasing constantly to about ½-inch diameter at the large (terminal) end; the weight was about 7 oz. The flare tubing was arranged in spiral form on a light metal frame, to burn inwards from the small end to the large end in about 40 minutes, with candlepower increasing gradually from about 20 to about 100. Tested on the ground, this flare burned satisfactorily except for severe dimming (perhaps due to conductive loss of heat) where the burning end of the tube passed the metal frame members. In about six night balloon tests this dimming was very apparent, though the light usually brightened again before it was lost to the theodolite. The best ascent reached an altitude of about 14,000 feet. In some ways this flare, with its tube hung horizontally, perpendicular to the slipstream, performed better than later models that were hung vertically. Some of our later flares performed satisfactorily under fan downdrafts up to 20 m p. h., yet went out in air tests. The wriggling, swinging, humping motion of the balloon rising at 400 yd./min. was something, apparently, that could not be duplicated by any tests on the ground

The second flare model, to obviate the dimming noted above and to simplify construction, was a straight, tapered tube. It was 25 inches long; the diameter was three-sixteenths inch at the lower (initial) end and thirteen-sixteenths inch at the upper end, whence a wire connected to the balloon string; the weight was 7 oz. and the burning time (horizontal in still air) 45 minutes; the candlepower increased gradually from about 30 at the start to around 150 at the end. About six night balloon tests showed that some fading had been eliminated, but considerable remained. All these flares blew out at altitudes below 10,000 feet, probably because the composition was too slow-burning and the initial diameter too small. Although the idea of a tapered tube and increasing candlepower was abandoned in succeeding models in order to simplify construction and reduce cost, it is believed to be worth further consideration.

The third and fourth flare models were straight, uniform cylindrical tubes, similar to railway flares but thinner and longer. Summarizing their characteristics:

No. 4 pyrotechnic balloon flare:
- Size: 11/16 inch (diameter) by 24 inches (length).
- Weight: 9½ oz. (270 g).
- Burning time: About 30 minutes.
- Candlepower: Average about 100.
- Candlepower for last minute: More than 500.

Flare with 16-inch balloon:
- Free lift: 42 oz. (1,190 g).
- Average rise rate: Around 400 yd./min., variable.
- 16-inch safety balloon inflated to 10 oz.

Tests with the model 3 flares showed considerable fading, apparently caused by temporary accumulations of ash from the pasteboard container tube as it burned away. These ash cones would stifle the flame somewhat for several seconds, then drop away. Consequently a faster-burning composition was used in model No. 4 (necessarily cutting down the burning time), with improved results.

Fourteen night-balloon tests were made with model 4 flares. They showed some fading, inseparable from any light source of this type; but the fading was not serious, and at lower levels the light was far brighter and clearer than any other balloon light, being visible for several minutes to the naked eye as a red, overbright star. The best altitude checked by double theodolite was 17,280 feet, when the light was about 6 miles distant in 17-mile winds. It disappeared suddenly from satisfactory brilliance. Ten of the flares went out similarly at altitudes between 9,000 and 16,000 feet. It is possible that lack of oxygen, which would be apparent at these altitudes, was the cause; though the composition includes its own oxygen, atmospheric oxygen might be necessary to the steady burning away of the pasteboard.

From the results described above, it appears that a still better flare might be built on the following specifications, using a fairly quick-burning composition: Tube, of diameter increasing from about eleven-sixteenths inch at lower (initial) end to about seven-eighths inch at upper end; candlepower gradually increasing from about 100 at start to about 500 at end; burning time, 25 minutes; weight, less than 12 oz. This desirable development, however, could not be undertaken in the time available.

The disadvantages of the flare are its unreliability (at present), its fairly heavy weight, and its serious fire hazard. In one or two of our tests, flares dropped several thousand feet due to wire breakage or premature balloon burst, and remained lighted all the way to the ground. We therefore used a strong (No. 16 copperclad steel) safety wire, and also a safety balloon on each of the later ascents. The function of the safety balloon, a 16-inch balloon inflated to 10 oz. free lift, was to hold the flare off the ground in case the lifting balloon burst; for least oscillation and most uniform ascent rate, the two balloons are preferably tied neck to neck. The advantages of the flare are its simplicity, ease of launching, and its outstandingly bright light when operating properly.

OBSERVATIONAL TECHNIQUE

Theodolite considerations.—All the tests described above were made with the standard theodolites in common use for upper wind observations. The observation of a planet or two (such as Jupiter and Saturn) with this instrument reveals that, optically, it leaves much to be desired. For high altitude night observations a larger objective—say 60 mm—would be far more satisfactory due to its increased light-gathering power and better definition. Two or three eyepieces, quickly interchangeable, say 10X, 20X, and 40X, should be provided. In daytime observations under a clear sky, a red filter can often be used to advantage, the balloon appearing as a bright red speck against a dark background. When trying for extreme altitude under unfavorable conditions (far out, the balloon appears as a very faint and evanescent speck), each theodolite should be manned by two men—one to follow the balloon and the other to read the scales.

For night work the reticule should be lighted internally and the scales lighted externally; the brightness of each electric bulb being controlled by a separate rheostat. Above 10,000 feet, under most conditions, two men should be on each theodolite. The theodolite must be screened from nearby surface lights that bother the observers.

Single versus double theodolite.—The average rise rates of 6-inch balloons have been thoroughly studied.[4] [5] Formulas have been developed giving rise rate in terms of balloon weight and free or total lift; with the small balloons these formulas are reasonably accurate. With the standard free lift, 4.66 oz. (137 g), a 6-inch balloon usually (but not always) ascends at a rate within ± 10 percent of 200 yd./min. Most of any series of ascents will be within the ± 10 percent limits, but occasionally a balloon will depart widely from the standard rate, perhaps by as much as 50 percent. It is apparent, therefore, that a one single-theodolite balloon ascent cannot be trusted blindly for accuracy (if accuracy in a given case is important), although in general the upper winds are given by single theodolite accurately enough for present-day uses. There is in aviation, however, some demand for more dependable upper winds expressed in magnetic degrees of azimuth.

Our tests with the 12-inch balloon showed that, in general, with a single theodolite, it would give results about as good as the 6-inch balloon. For dependable upper wind observations to high altitudes with the 16-inch balloon (and no smaller balloon dependably reaches these altitudes), our tests showed double-theodolite observations to be very desirable.

Double-theodolite observations mean, in optimum practice, three theodolite positions located to form two alternate base lines roughly at right angles. For best results all three theodolites should be manned, the base line being changed as necessitated by the balloon drift. Even for high-altitude observations, 2-mile base lines usually suffice. All theodolite stations should preferably be connected to the plotting board by dependable wire telephone.

With a well designed plotting board, double or triple theodolite determination of upper winds is simple and easy. The board used in most of our tests was developed as the result of several years' experience at Aberdeen Proving Ground. The fixed center pin represents the balloon. From this pin radiate three arms (set with reference to a large degree circle on the board) representing azimuth from station A, azimuth from station B, and elevation from station A. The station A azimuth arm is provided with a perpendicular altitude arm (set against the station A elevation arm). Any desired base line can be chosen from a four-theodolite network; on the board a base line (or double or quadruple base line) is represented by a small ruler-like straight edge clamped to a drafting machine which holds it always parallel to its actual azimuth wherever it is moved on the board. Base lines can be switched during an ascent, and velocities of upper winds are determined as the balloon rises to new levels without any delay.

High-altitude upper-wind possibilities.—Regardless of aviation or other demand, it would not seem possible to put in high-altitude facilities at each of the eighty-odd upper-wind stations now operated by Weather Bureau, military and naval, and private services in the United States. One might visualize, rather, a limited network of 15 or 20 high-altitude, upper-wind stations superposed on the denser low-altitude network. The high-altitude upper, wind stations, indeed, might coincide with the present airplane-sounding stations, which should change gradually to radio-sounding-balloon stations in any case. Eventually, when better solutions are found to the difficult radio-pilot-balloon problem, the same stations could be used for this purpose also. Thus 15 or 20 high-altitude upper-air stations scattered over the United States might eventually determine upper winds to 30,000 feet altitude by balloons and light sources similar to those described above, under clear skies or cirriform clouds; they might determine upper winds by radio-pilot balloon through lower clouds or poor visibility; and they might determine air-mass characteristics from pressure, temperature, and humidity values given by radio-sounding balloons.

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